Lessons and Recommendations for Board Level Testing with Protons

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Acronyms

DUT	Device Under Test
ISS	International Space Station
JPL	Jet Propulsion Laboratory
LEO	Low Earth Orbit
LET	Linear Energy Transfer
MeV	million electron-Volts
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
NASA	National Aeronautics and Space Administration
NEPP	NASA Electronic Parts and Packaging Program
SEE	Single-Event Effects
SEL	Single-Event Latchup
TID	Total Ionizing Dose
TRIUMF	Tri-University Meson Facility
UUT	Unit Under Test
Vgs	gate-to-source Voltage

Outline

- What is board-level testing with protons
- What are the potential problems
- It has be useful… why?
- Test planning
- Test preparation
- Test execution
- Test interpretation
- Lessons Learned (note, not in paper)
- Summary

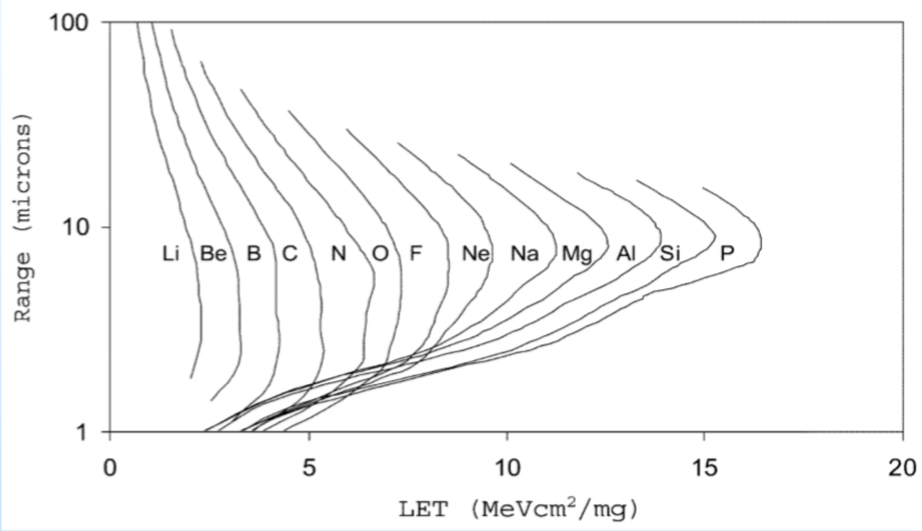
Board Level Testing Done Right

- Is there a simple and cheap way to do single-event effects testing of a board, all at once?
  - It depends…
- If you have the right combination of
  - Mild environment
  - Short duration
  - Willingness to accept risk
- What do you do?
  - Test with high (~200 MeV) protons. (Next slide…)
- How good is it?
  - Questionable – worse if done wrong. (Rest of the talk.)

Why 200 MeV?

- Protons are a proxy for heavy ions because their secondaries give LETs in excess 14 MeV-cm^2/mg.
- The higher the energy of the beam, the higher the energy (not LET) of the secondaries.
  – Total deposited energy is higher, so they are more space-like.
- Higher energy is better.
  – Increased range improves damaging SEE effectiveness
  – Higher LETs in space are mostly Fe – missing in proton secondaries…
- But higher energy is not readily available, and doesn't really improve things much.
  – Max LET is still only around 14 MeV-cm^2/mg
  – Overall range is better
  – Options like Los Alamos (800 MeV) and TRIUMF (500 MeV) exist.

Heimstra, 2003 – for 500 MeV protons



200 MeV Is a Sweet-Spot, but…

- **It is good for proton secondaries.**
- **Higher proton energy also reduces dose.**
- **It puts SEE test facilities in-line with medical facilities.**

California Protons
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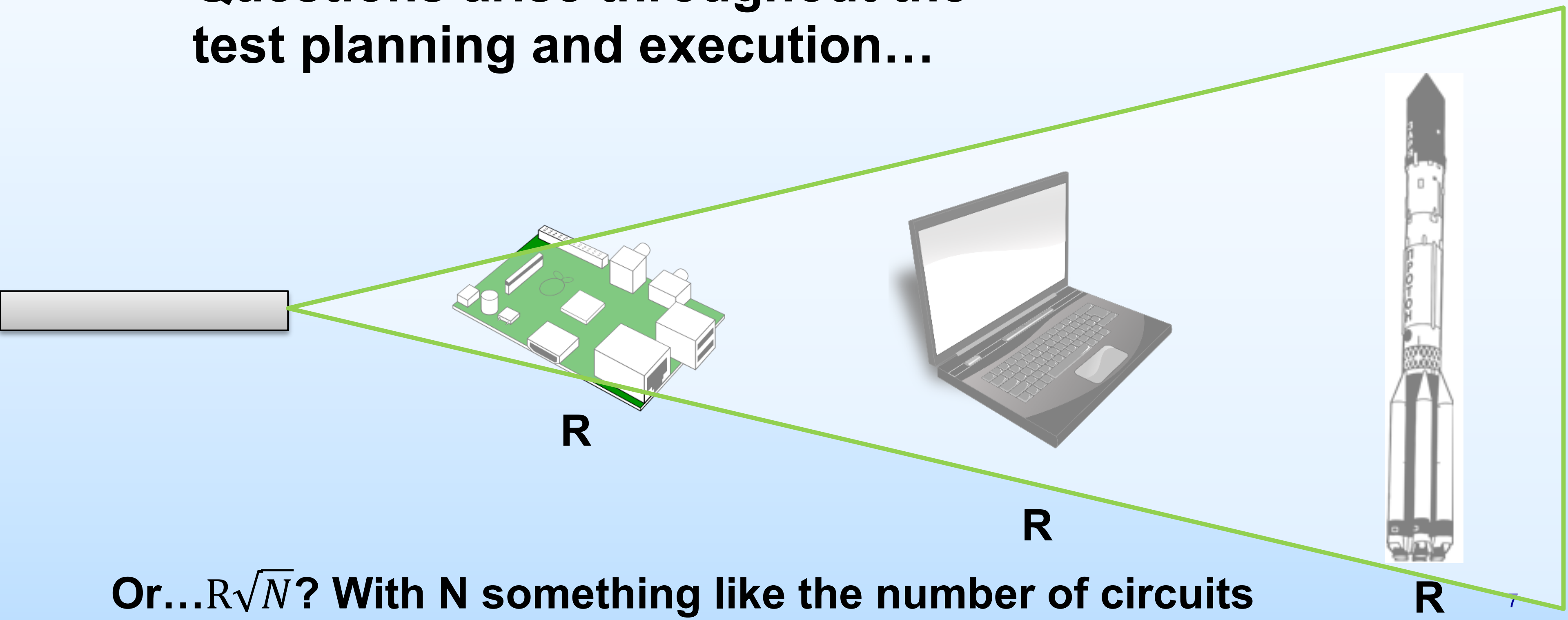
- **Dozens of facilities…**

There Are Many Potential Issues

- Test results are not well-defined, because system size can be arbitrary
  – Assume the test results in a system rate of R…
- Questions arise throughout the test planning and execution…



Or…$R\sqrt{N}$? With N something like the number of circuits

Scorecard

- The proton board-level testing method has a history of success
- But it is not supported by solid engineering or physics

- Have previous practitioners have been conservative in using the approach?
  - Maybe
- Have we been lucky that systems worked well?
  - Probably. Might even be “accidentally” mitigating damage
  - NASA has only used this in non-critical systems
- Have some failures not been reported?
  - Difficult to say on the NASA side – probably logged, but not necessarily brought to attention of radiation people
  - Suspect situation is worse in most other organizations

Moving Forward

- Approach is driven by data on worst parts – is there really enough data yet? Most likely no.
  - Why would anyone take proton data on a part that is observed to have SEL with an LET of less than 10?
  - Why take heavy ion data in a part has SEL with protons?

- Given the inherent limitations of the method, how can we achieve the best results?

- We will explore some specific situations and a couple lessons learned.

Test Planning

- **You can only reliably achieve 0.01-0.003 damaging events per system day in LEO – if this is not good enough, heavy ions are required.**
  - **Higher assurance claims are not grounded in physics or engineering, but may “seem” to work.**
- **Test early in the cycle, so the results can be used. Don’t just hope the results will be ok.**
- **Test the same board as the flight board – same parts – manufacturer and part number should match.**
  - **“good engineering” says they really need to be the same, but people are often trying to justify “similar devices”**
- **Reserve beam time 8 months ahead of time. Proton beam time is difficult to schedule.**

- **Use beam energy of at least 190 MeV in order to keep TID on articles below 1 krad(Si) when irradiating to $1{\times}10^{10}/cm^2$.**

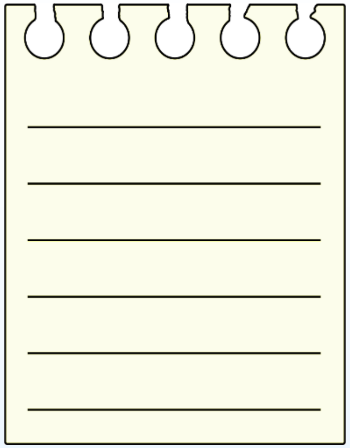
Test Preparation

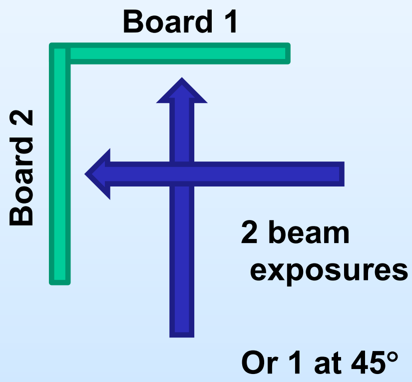
- Contact facility to get details and recommendations for use of the facility.
- If possible, perform a walkthrough of the facility a few weeks before the actual test.
- Discuss beam parameters with the facility: time and space structure, flux & flux range, etc.
- Determine if the facility can accommodate the full size of your hardware.
- Hardware usually cannot ship for at least a few days after the test.
- Test the full setup (including full cable length) before arriving at the facility.
- More info in the paper.

Photo: Irradiation of iPad at UC Davis – due to spot size, multiple irradiation sites were necessary.

Test Execution

- Keep a test log including:
  - run number
  - DUT/UUT identification
  - time, fluence, flux
  - etc…
- Use cooling fans instead of heatsinks (keep fans out of beam) – if possible
- Avoid stacks of 6 or more boards
- Test with proton beam normal to the test boards
  - If boards are mounted 90 degrees to each other, test multiple units with beam normal to the board surfaces
  - If angles are used, multiply the fluence delivered by the cosine of the angle of incidence.
- Use beam exposures with duration > 60 s, with at least 10 s between events, or consider slowing down the beam.





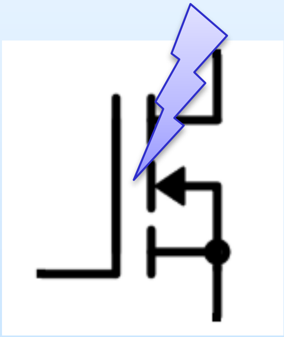
More in the paper

Test Interpretation/Reporting

- It would be great to have a detailed test report, but a simple summary of the test and observations should be a minimum
- If damaging events are NOT SEEN, use the following estimations:
  – 0.01 events/system-day for $1\times10^{10}/cm^2$ or
  – 0.003 events/system-day for $1\times10^{11}/cm^2$
- For non-damaging events (transients, bit upsets, etc.)
  – N * 0.0005 events/system-day for $1\times10^{10}/cm^2$ where N is the number of observed events.
  – This scales for higher test fluences.
- If damaging events are seen, use the larger of estimates above.

Lesson: Be Ready to Use Test Results

- During one board level test, a permanent failure was observed.
- Because the schematics were available, and a radiation expert (familiar with parts list reviews) was on hand…
  - A list of at-risk parts was identified
  - List was narrowed down by circuit implementation
  - Further narrowed down by failure (no power delivered)
- Identified a MOSFET operating at >80% of rated Vgs in the design
  - Recommendation is < 50%
  - Circuit testing showed the MOSFET had failed
- Were able to swap in alternate (with higher Vgs) that enabled system to work and not fail in radiation.



Lesson Learned: Flight-Like Operation

- Test approach was to have all board operations cycled through during exposure
  - Complex applications made to target all board operations – multiple applications
- The board was dependent on a commercial PowerPC processor running Linux, with the operations in a test program.
- Actual observations were primarily kernel panics due to unhandled exceptions.
  - No value was obtained from different software applications
- None of the special test applications showed SEEs because operating system was primary weak point.
- Lesson: Don’t develop a lot of extra test operations outside of flight use

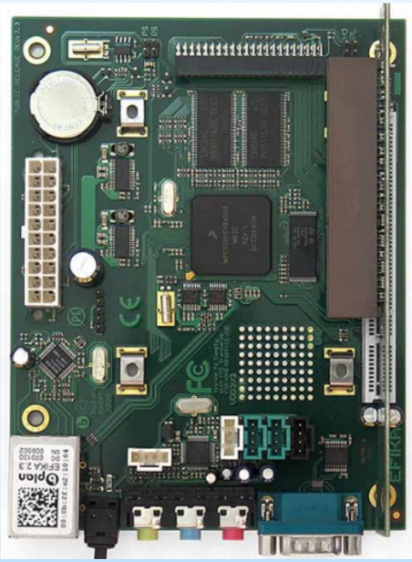


Photo: Efika 400MHz PowerPC SBC

Summary

- Proton testing can be used in lieu of normal assurance (including heavy ions) if
  - Environment is weak (i.e. LEO, ISS, Mars Surface)
  - Missing is short or can handle high risk
- Physics and engineering both suggest fairly high rates for possible damaging SEE
  - 0.01 to 0.003/system-day for ISS orbit when testing with $1{\times}10^{10}$-$1{\times}10^{11}$/cm^{2}.
- To ensure the test method provides results that can be trusted to these levels, we provide recommendations.
  - Test Planning
  - Test Preparation
  - Test Execution
  - Text Interpretation/Analysis